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# An Analysis of the Wear Behavior of SiC Whisker Reinforced Alumina From 25 to 1200 °C

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# AN ANALYSIS OF THE WEAR BEHAVIOR OF SiC WHISKER REINFORCED ALUMINA FROM 25 TO 1200 °C

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## SUMMARY

The following paper describes a model for predicting the wear behavior of whisker reinforced ceramics. The model has been successfully applied to a silicon carbide whisker reinforced alumina ceramic composite subjected to sliding contact. The model compares the frictional forces on the whiskers due to sliding, which act to pull or push them out of the matrix, to the clamping or compressive forces on the whiskers due to the matrix, which act to hold the whiskers in the composite. At low temperatures, the whiskers are held strongly in the matrix and are fractured into pieces during the wear process along with the matrix. At elevated temperatures differential thermal expansion between the whiskers and matrix can cause "loosening" of the whiskers and lead to pullout during the wear process and to higher wear.

The model, which represents the combination of an elastic stress analysis and a friction heating analysis, predicts a transition temperature at which the strength of the whiskers equals the "clamping" force holding them in the matrix. Above the transition the whiskers are pulled out of the matrix during sliding, and below the transition the whiskers are simply fractured. The existence of the transition gives rise to a dual wear mode or mechanism behavior for this material which has been observed in laboratory experiments. The results from this model correlate well with experimentally observed behavior indicating that the model may be useful in obtaining a better understanding of material behavior and in making material improvements.

## INTRODUCTION

The lack of a detailed understanding of how ceramics wear, especially under extreme conditions such as high temperatures, loads and speeds has been an obstacle to their successful use in tribological applications. Depending upon the sliding conditions, the wear may be due to fracture, plastic deformation and even chemical attack. Because many anticipated uses for ceramics include extreme applications, such as high temperature engine components and high speed cutting tools, it is important to understand ceramics' wear behavior under realistic conditions (ref. 1).

The traditional approach to understanding the wear of ceramics is to model them as brittle materials and apply fracture mechanics theory. Wear models developed in this way tend to be useful for predicting room temperature wear behavior of monolithic ceramics but are not usually suitable for high temperatures or for complex ceramic composite materials like whisker toughened ceramics. Although their wear behavior is usually more complex than monolithic ceramics, it is useful to study whisker reinforced ceramics because their superior toughness makes them attractive engineering materials.

Recent tribological data indicates that the wear of unlubricated ceramics can be quite high (ref. 2). Models which merely predict wear rates may aid our ability to anticipate and accommodate for wear but these models do little to help improve the materials. Because of these analytical shortcomings, much work with ceramics has been to experimentally quantify their tribological behavior and to develop lubricating methods using an experimental approach.

One material system which has received considerable attention as a candidate for structural and sliding applications is whisker reinforced SiCw-$Al_2O_3$ ceramic composites. This ceramic composite is comprised of an alumina matrix with quasi-randomly dispersed SiC whiskers which act as crack deflectors. Tribotests of the composite indicate that it has good wear resistance over a wide temperature range and that it has toughness superior to both monolithic $Al_2O_3$ or SiC (ref. 3). Because of the composite's desirable mechanical properties it is useful to further study its wear behavior. Also, since this material is a candidate for heat engine applications and high speed cutting tools (which must endure high temperatures due to frictional heating), it is important to understand its wear behavior at high temperatures (ref. 4).

In a previous study by this author, the wear behavior of a SiCw-$Al_2O_3$ composite was studied experimentally by analyzing pin-on-disk wear specimens and wear debris using optical, scanning electron and transmission electron microscopy (ref. 5). In that work, it was determined that the material experiences dual wear modes. At lower temperatures the material wears in a typical brittle manner. Namely, cracks form near the sliding surface and propagate both around and through the whiskers. In this case, brittle fracture theory may be directly applicable to describing the wear behavior. At high temperatures, however, the wear mode changes to one in which the whiskers are pulled out of the matrix unbroken and then the alumina matrix, riddled with holes left from the pulled out whiskers, easily fractures leading to higher wear rates.

The reason for this dual wear mode behavior was attributed to large thermal expansion mismatch between the SiC whiskers ($\alpha = 4.0\times10^{-6}/^\circ C$) and the $Al_2O_3$ matrix ($\alpha = 8.0\times10^{-6}/^\circ C$). Upon cooling the material (following hot consolidation) to lower temperatures, the whiskers are in compression and strongly held by the matrix and cannot be pulled out during the sliding process. Thus, during sliding at low temperatures the whiskers are fractured and the wear is characterized by brittle behavior. At higher temperatures, the compressive stress is relieved by thermal expansion and the whiskers are not as strongly held by the matrix and thus can be pulled out more easily during sliding giving rise to a second wear mode, namely whisker pull out and subsequent material fracture, and higher wear.

The major conclusion from this experimental work is that under these sliding conditions the SiCw-$Al_2O_3$ composite exhibits a dual wear mode tribobehavior. Therefore, any modeling of wear mechanisms must contain and explain the reason for the two wear modes.

The following analysis explains the experimental results by combining a thermal stress analysis with a tribothermal analysis. A model is then developed to describe the dual wear mode experimentally observed. In addition to determining why this dual wear mode behavior exists, the analysis shows which material and test parameters have significant effects on tribological performance.

## Materials

The material system studied here is a SiC whisker reinforced $Al_2O_3$ composite. The $Al_2O_3$ composite contains 25 vol % SiC whiskers which are ≈0.75 μm in diameter and 10 to 60 μm long. Although the experimental work done previously specifically tested a 25 vol % SiCw-$Al_2O_3$ composite other compositions which have good mechanical properties contain from 10 to 40 vol % SiC whiskers. Table I gives the material's detailed composition and the manufacturer's strength/property data. Data for partially stabilized $ZrO_2$ is given for comparison.

The composite is made by mixing high purity (>99.95 percent pure with traces of iron and silicon) alumina powder with single crystal SiC whiskers followed by hot pressing at about 1600 °C. During consolidation, many of the whiskers preferentially align themselves in a plane perpendicular to the pressing direction (ref. 6). The tribocontact modeled in this paper has the rubbing surface parallel to the whisker planes. See figure 1.

# THERMOMECHANICAL WEAR ANALYSIS

## Nomenclature

| | |
|---|---|
| $F_T$ | total friction force in sliding contact, N |
| $F_{BREAK}$ | calculated fracture force for SiC whisker, mN |
| WTS | whisker tensile strength, GPa |
| $\sigma_{csw}$ | compressive stress on whisker completely embedded in matrix of an 18 vol % SiCw-$Al_2O_3$ composite, MPa |
| D | whisker diameter |
| L | whisker length |
| $\mu_{mw}$ | static friction coefficient between matrix and whisker (assumed to be ≈1.0) |
| $F_{PULLOUT}$ | force required to pull out a whisker at the sliding surface and only partially (≈1/2 embedded) surrounded by the matrix |
| $C_{vol}$ | compressive stress coefficient for the effect of whisker volume percent |

| | |
|---|---|
| $\sigma_{net}$ | compressive stress on an embedded whisker as a function of temperature and whisker volume percent, MPa |
| $\mu$ | sliding friction coefficient |
| $F_N$ | applied normal test load, N |
| K | thermal conductivity, $W/m^2\ °C$ |
| v | sliding velocity, m/s |
| $T_{test}$ | ambient test temperature, °C |
| $T_S$ | calculated surface region temperature, °C |
| $r_o$ | wear scar radius, m |
| a | thermal diffusivity, $m^2/s$ |

## Model

The following analysis models the wear behavior of the SiCw-$Al_2O_3$ composite through a force balance on the whiskers coupled with the effects of bulk and frictional heating due to sliding. In the model, the sliding friction force ($F_T$) will be compared to the force required to fracture a whisker ($F_{BREAK}$) and to the force required to pull out a whisker ($F_{PULLOUT}$) as a function of temperature in order to explain the dual wear mode. The model will include the effect of material parameters (such as thermal expansion coefficients, thermal conductivity, whisker strength, etc.) as well as the effect of tribological and test parameters (such as friction coefficient, sliding speed, load and temperature) on the wear behavior and may aid in making steps to improve the composite.

Because the experimental program used a pin-on-disk configuration to generate wear conditions, the pin-on-disk configuration will be modeled here. Figure 2 shows, schematically, the wear specimens. It is assumed that the whiskers are pulled or pushed out of the matrix by the high frictional shear stresses present at the sliding interface or by a large counterface asperity as shown in an exaggerated fashion in figure 2.

The tangential forces present in the sliding contact which can act to fracture or pull out whiskers are appreciable and are approximated by the experimentally measured friction force, $F_T = \mu * F_N$. For our tests, $\mu \approx 0.7$ and $F_N = 26.5$ N so that $F_T \approx 18.6$ N. This force ($F_T$) is much greater than the force required to break a whisker ($F_{BREAK}$), which can be estimated as the whisker strength multiplied by the whisker cross sectional area.

No data exists for the exact strength of the SiC whiskers used in this composite, however, Becker and Wei estimate the whisker tensile strength, WTS, to be about 7 GPa (ref. 7). Their estimate is based upon tensile tests of like diameter, longer SiC fibers and larger diameter (4 $\mu$m) but comparable length whiskers. Using this strength estimate (WTS = 7 Gpa) and assuming that the average whisker is 0.75 $\mu$m in diameter, the force required to break a whisker ($F_{BREAK}$) is about 3.1 mN.

Although this type of calculation is approximate, it can be readily seen that the forces present in the sliding contact, namely $F_T$, are appreciable compared to the strength of the whiskers and, thus, whiskers are broken. (Even when the total force, $F_T$, is normalized by the ratio of the initial tribological contact area to the exposed whisker cross section area, L $*$ D, the tangential friction force on a whisker is still more than five times greater than $F_{BREAK}$). Hence, the sliding process generates wear debris. To summarize:

$$F_T >> F_{BREAK} \tag{1}$$

where $F_T$ is the force available at the surface by the counterface to pull (or push) a whisker out of the matrix and $F_{BREAK}$ is the calculated force necessary to break a SiC whisker.

When an asperity, or simply the counterface, contacts a whisker (as in fig. 2), either the whisker can fracture as is seen experimentally in low temperature sliding tests or the whisker can be pulled out of the matrix as is observed during sliding at higher temperatures.

The force required to pull out a fully embedded whisker is equal to the compressive stresses acting on the whisker due to the matrix ($\sigma_{CSW}$), multiplied by both the whisker surface area ($\pi$DL) and the friction coefficient between the matrix and the whisker, $\mu_{mw}$.

Whiskers that are pulled from the matrix either by a counterface asperity or merely by the tangential friction forces are necessarily exposed to the sliding surface. As such they cannot be completely embedded in or surrounded by the matrix. Therefore, the actual surface area upon which the compressive matrix stresses act on the whiskers is only a fraction of the total area, $\pi$DL. If a whisker were completely exposed to the sliding surface, the surface area acted upon by the matrix would be zero and if completely surrounded, the surface area would be equal to $\pi$DL. For the following analysis, it will be assumed that the whiskers are only partially exposed and that the compressive matrix stresses act upon about one half of the total whisker surface area or $\pi$DL/2.

By comparing the forces required to pull out a whisker, $F_{PULLOUT}$, to the force required to fracture a whisker, $F_{BREAK}$, a prediction of the outcome of a whisker-counterface interaction can be made (i.e., the whisker is pulled out or broken).

For this analysis, it is assumed that the bond between the whiskers and the matrix is purely mechanical, arising from friction forces. Chemical bonding is neglected for this material system and it if exists, it is probably small. This assumption is based upon the widely held viewpoint that for a ceramic matrix composite to show improved toughness, as this composite does, the chemical bonding between the whiskers and the matrix is small. Therefore, cracks are branched and deflected by the whiskers rather than propagating through them. Thus, the force required to remove a whisker from the surrounding matrix, ($F_{PULLOUT}$), is equal to the frictional forces on the whiskers. For simplicity, $\mu_{mw}$ is considered to be about 1.0 which is typical for unlubricated ceramics and hence will be dropped in the following equations.

At lower temperatures the compressive stresses on the whiskers due to the matrix are very high (on the order of 750 MPa) and thus the force required to pull out a whisker ($F_{PULLOUT}$) is greater than the whisker fracture force ($F_{BREAK}$) strength:

$$F_{PULLOUT} > F_{BREAK}$$

$$(\sigma_{csw}) * (\pi DL/2) > WTS * (\pi D^2/4) \tag{2}$$

where WTS is the whisker tensile strength, D is the diameter, and L is the average whisker length.

Under this condition, characteristic of low temperatures, the whiskers are fractured rather than being pulled out during sliding, and wear follows brittle behavior.

At higher temperatures, thermal expansion of the matrix reduces the compressive stress on the whiskers and the inequality reverses so that:

$$F_{PULLOUT} > F_{BREAK}$$

$$(\sigma_{csw}) * \pi DL/2 > (WTS) * (\pi D^2/4) \tag{3}$$

Under this condition, the whiskers are pulled out of the matrix during sliding. The second wear process, namely whisker pullout, which occurs at higher temperatures, leaves the matrix riddled with holes, or empty whisker pockets, which act as flaws or fracture initiation sites and leads to higher wear.

The main parameter affecting the compressive stresses on the whiskers is the near surface temperature of the specimens (i.e., within a few whisker diameters from the surface). The temperature is, in turn, affected by the tribological and test parameters such as ambient test temperature, friction coefficient, load, and velocity as well as material parameters such as thermal conductivity and diffusivity.

## Thermoelastic Stress Analysis

Since brittle materials, such as this composite, behave elastically up to the fracture point, we can determine the stresses in the material using elasticity theory. The magnitude of the compressive stresses on the whiskers and the tensile stresses on the matrix have been experimentally measured and analytically modeled (refs. 8 to 10). The models are based upon the application of Hooke's Law in three dimensions where the residual thermal strains are calculated by elasticity theory.

In general, the whiskers are modeled as being completely embedded in an infinite isotropic ceramic matrix. Although in reality the elastic constants for the whiskers are not isotropic, when isotropic values are used reasonable results are obtained (i.e., they agree with other more rigorous tests such as experimental stress analysis). The analytical method and results presented here are based upon an original analysis by Eshelby (ref. 11). To compensate for whisker interactions and nonisotropic elastic constants, a self-consistent approach was used, i.e., the model is of a single whisker completely embedded in an infinite matrix which has the elastic properties of the bulk SiCw-$Al_2O_3$ composite.

The analysis method, first outlined by Mori and Tanaka (ref. 12), was applied to this SiCw-$Al_2O_3$ material by Majumdar and Kupperman (ref. 9). The analysis consists of setting up a three-dimensional matrix of Hooke's Law and following the stress and strain fields in a SiC whisker as temperature is changed.

Majumdar and Kupperman (ref. 9) applied this approach to the SiCw-$Al_2O_3$ material system and some of their results are shown in figure 3. As can be clearly seen from the figure, the compressive stresses on the whisker are highest at room temperature and decrease linearly with temperature. Their analytical results were in excellent agreement with experimental stress analysis results obtained by neutron diffraction techniques. This helps increase confidence in their stress analysis method.

The results of the analytical stress analysis from reference 9 can be summarized as follows. During cooling from the initial consolidation temperatures ($\approx$1600 °C) differences in the coefficient of thermal expansion (CTE) between the SiC whiskers and the $Al_2O_3$ matrix cause thermal stresses to form which are relieved by matrix creep. At temperatures below about 1350 °C, however, the matrix is stiffened and creep is no longer a dominant factor in stress relief thus thermal stresses develop. Because the CTE for the whiskers is about one-half that of the matrix the whiskers are placed in compression. As the temperature further decreases, the residual stresses at the whisker/matrix interface continue to rise in a more or less linear fashion. It is this compressive stress on the whiskers which helps to hold them in the matrix during sliding.

The following curve-fit equation describes the variation of whisker compressive stresses with temperature:

$$\sigma_{csw} = 1000 \text{ MPa} - 0.741 \text{ MPa}/{}^\circ\text{C} \times T \tag{4}$$

for a composite containing 18 percent by volume SiC whiskers.

Majumdar et al. (ref. 10) extended their analyses to include the effect of whisker volume percent. The average strains (and hence stresses) were found to decrease with SiC content in a more or less linear fashion as shown in figure 4. The decrease in stress was attributed to a dilution effect of the matrix stress effect by the addition of SiC whiskers.

A curve fit for this effect, taken from figure 4 is given by the dimensionless coefficient as follows:

$$C_{vol} = [1 - 0.01449(\text{Percent SiC whiskers} - 18 \text{ percent})] \tag{5}$$

Equation (5) can be considered accurate for compositions ranging from about 15 to 40 vol % SiC whiskers.

By combining equations (4) and (5) with the effect of bulk temperature, we get an equation which relates the compressive stresses on a fully embedded whisker with temperature and composition.

$$\sigma_{net}(T, \text{Percent SiCw}) = \sigma_{csw} * C_{vol} \tag{6}$$

or

$$\sigma_{net}(T, \text{Percent SiC whiskers}) =$$

$$[1000 \text{ MPa} - 0.741 \text{ MPa}/{}^\circ\text{C} \times T]\{1 - 0.01449(\text{Percent SiC} - 18 \text{ percent})\}$$

where $\sigma_{net}$ represents the stress on a fully embedded whisker due to the matrix as a function of temperature and composite whisker content. To use equation (6) to calculate $F_{PULLOUT}$, equation (2) can be employed, substituting $\sigma_{net}$ for $\sigma_{csw}$.

From a tribological point of view, the key aspects of equation (6) are that the compressive stresses on the whiskers decrease linearly with temperature and with volume percent SiC whiskers.

## Tribothermal Analysis

If the composite were applied in a static situation, i.e., without sliding, the above analysis would be sufficient to describe the stress state of the whiskers, assuming that the sample is in thermal equilibrium with the ambient. However, during sliding, frictional heating can greatly increase the near surface temperatures, significantly altering the whisker stresses and, hence, potentially the tribological properties of the material.

Many researchers have studied the problem of determining surface temperatures and near surface region temperature rise which occur as a consequence of frictional heating (refs. 13 and 14). Although specific details do vary, it is generally accepted that the temperature rise is a function of such variables as load, speed, friction coefficient, thermal conductivity and diffusivity as well as the type of environment present.

To describe the temperature rise occurring for pin specimens studied here, an analysis by Ashby (ref. 14) has been found to be useful. Figure 5 shows the physical situation described by Ashby's model which is based upon the assumption that the frictional heating is conducted away from the sliding contact into the pin and its holder and also into the disk. Convection is neglected and the mean heat diffusion distance (the near surface region of the sliding contact) has been approximated by 1.6 times the contact radius, $r_o$, as suggested by Ashby (ref. 14). The following equation mathematically describes the "bulk" heating of the specimens, i.e., the temperature rise of the pin in the region near the scar.

$$T_S = T_{TEST} + \left(\frac{\mu F_N V}{2\pi^{1/2} K r_o}\right) * \left[\frac{1 + \pi}{2 \tan^{-1}\left(\frac{2\pi a}{V r_o}\right)^{1/2}}\right]^{-1} \tag{7}$$

where

| | |
|---|---|
| $\mu$ | friction coefficient |
| $F_N$ | normal load force |
| K | thermal conductivity |
| V | sliding velocity |
| $T_{TEST}$ | ambient test temperature |
| $r_o$ | wear scar radius |
| a | thermal diffusivity of the material |

This equation considers both material parameters and test parameters. For the analysis presented in this paper, the material parameters are essentially constant. Therefore, the important variables are load, speed, friction coefficient and $T_{TEST}$. As these are increased, the near surface region temperature increases and thus the compressive stresses on the whiskers decrease. From these considerations, it is possible to have a room temperature test, which, due to higher surface temperatures caused by frictional heating, exhibits whisker pullout.

The magnitude of the frictional heating effects can be seen by examining Table II. This table shows the test conditions and calculated surface temperatures for the tests conducted in the experimental work (ref. 5). It can be seen that even at moderate loads and speeds, the frictional temperatures rise above the ambient by about 400 to 500 °C. This heating can greatly influence the wear mode of the materials by changing the stresses on the whiskers in the region of sliding.

## Discussion of Analytical Results

The results of the preceding analyses and the implications on the wear behavior are illustrated graphically in figure 6 which shows plots for both the required pullout force ($F_{PULLOUT}$) on the whiskers and the whisker fracture force ($F_{BREAK}$) versus the near surface temperatures for a 25 vol % SiCw-$Al_2O_3$. The inequality reversal or crossover point, at about 1200 °C, between the whisker fracture force ($F_{BREAK}$) and the compressive forces on the whiskers ($F_{PULLOUT}$), shown graphically in figure 6 as the "transition region" and described by equations (2) and (3), gives a plausible reason why dual wear mechanisms (namely whisker pull-out or generalized fracture) exist for the composite material. As described previously, when the whisker fracture force is less than the compressive forces holding the whiskers in the matrix, interactions with the sliding counterface will fracture the whiskers. This behavior occurs at temperatures below 1200 °C. At temperatures above about 1200 °C, the compressive forces holding the whiskers in the matrix drop below the whisker fracture force and interactions with the counterface will result in whisker pull-out rather than fractures.

The width of the transition region is based upon tribodata scatter (namely friction variation) and uncertainties in the analysis and is typically $\approx\pm100$ °C. One factor which can have a significant effect on the transition point is whisker length. Its effect can be seen in equations (2) and (3). Since the whiskers range in length from about 10 to 60 $\mu$m, the pull out force and hence the transition point can vary significantly. See figure 7. From this figure it can be seen that the transition point changes from about 1000 °C for short (10 $\mu$m) whiskers to about 1300 °C for long (60 $\mu$m) whiskers. Thus one would expect composites made with predominantly shorter whiskers to suffer from whisker pull out at lower temperatures than composites made with longer whiskers. Composites made with longer whiskers, however, would not necessarily be optimum since other mechanical properties such as toughness and processing ease can be degraded with unduly long whiskers.

By examining the equations describing the stress conditions on the whiskers, some insight into the effects of variables on the potential wear behavior can be determined. For example, equation (6) relates the stresses on the whiskers as a function of bulk temperature and composite whisker content. By varying the whisker content from 18 to 40 percent the transition temperature decreases by approximately 350 °C. See figure 8.

Therefore, the whisker content of the composite may have a significant effect in determining the wear mode. This effect needs to be verified experimentally, however, as changes in whisker content can also affect the toughness in an inconsistent manner thereby having an unknown effect on triboperformance.

Changes in test conditions, such as load, velocity and ambient test temperature directly affect the calculated sliding temperature as in equation (7). As these variables increase, the sliding temperatures increase also. Of course, increases in friction also increase the temperature indicating that lubricating the sliding contact will reduce the temperature and may improve the wear behavior.

## Comparison to Experimental Data

Comparing the analytical results to experimental results is simply a matter of calculating the near surface region temperatures for sliding tests conducted with this material and seeing whether the model correctly predicts the experimentally determined wear mode.

Table 3 shows the calculated temperatures and experimentally observed wear modes for tests conducted at ambient temperatures of 25, 600, 800, and 1200 °C. These results are also depicted on figure 6 in which the vertical dotted lines represent the calculated temperatures for the ambient test temperatures of 25, 600, 800, and 1200 °C. The observed wear mode is determined by the relative magnitudes of the whisker breaking force and the whisker pullout force. For example, at temperatures below the transition point of 1200 °C, the force required for whisker pullout, $F_{PULLOUT}$, is greater than the force required to break a whisker, $F_{BREAK}$, and therefore whisker fracture is observed. Above 1200 °C the force required for pullout is smaller than the whisker breaking force and, therefore, whisker pullout is observed. Since the model correlates well with the wear behavior in the experimental tests it may be useful in predicting the wear behavior of other similar materials under a wide variety of test conditions.

One interesting point, which requires further investigations, is that the wear factors experimentally determined in previous work indicate a maximum at a calculated sliding temperature of 1071 °C. This temperature is near the transition point of ≈1200 °C. There may be a relationship between maximum wear and the transition in wear behavior. Other authors have also measured wear maximums with the alumina-silicon carbide composite (ref. 15).

Furthermore, the model defines the limits or envelope of useable test conditions, beyond which the materials wear properties degrade. By using the analysis presented, the effects of a wide variety of variables on the wear mode can be more or less predicted.

It is clear that the wear behavior of whisker reinforced ceramics is complex. The addition of the second phase (SiCw) radically alters the materials properties. Although the composite system may be more difficult to study, its superior properties (toughness and wear resistance) make it an ideal candidate for demanding applications. Therefore it is worthwhile to conduct research in this area.

## RESULTS SUMMARY AND CONCLUSIONS

The following statements and conclusions can be made based upon this work:

1. A model for predicting the wear behavior of whisker toughened ceramics, based upon thermoelastic stress and tribothermal analyses, has been developed and successfully applied to an $Al_2O_3$-SiC system.

2. The model provides a reason for the experimentally observed dual wear mode behavior of this material system. The dual wear modes are due to the change in the inequality between the whisker fracture strength and the compressive clamping forces on the whiskers from the matrix.

3. The model predicts that the wear mode is a function of the whisker stress state, which, in turn, is a function of test temperature and triboconditions.

4. This model presented here correlates well with experimental evidence and may be useful in making further material improvements.

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TABLE I. - MANUFACTURER'S STRENGTH AND PROPERTY DATA[a]

| Property | Material | | | |
|---|---|---|---|---|
| | $Al_2O_3$ | SiC | $Al_2O_3$-SiC | $ZrO_2$ |
| Density, g/cc | 3.9 | 3.1 | 3.74 | 5.7 |
| Young's modulus, GPa | 386 | 406 | 393 | 200 |
| Vickers hardness, $kg/mm^2$ | 2000 | 2800 | 2125 | 1050 |
| Toughness, $MPa/\sqrt{m}$ | 4.2 | 3.8 | 8.8 | 8.2 |
| Thermal expansion coefficient, /°C | $8.0\times10^{-6}$ | $4.0\times10^{-6}$ | $6.0\times10^{-6}$ | $9.2\times10^{-6}$ |
| 4 pt. bend strength, MPa @ R.T. | 344 | 448 | 641 | 630 |
| Poisson's ratio | 0.23 | 0.12 | 0.23 | 0.23 |
| Thermal conductivity, W/m °C | 22 | 12.5 | 22.3 | 2.0 |
| Thermal diffusivity, $m^2/s$ | $8.0\times10^{-6}$ | $6.0\times10^{-2}$ | $1.35\times10^{-5}$ | $7.0\times10^{-7}$ |

[a]ARCO Chemical Co., Green, SC and Carborundum Co., Niagra Falls, NY.

TABLE II. - TEST CONDITIONS AND CALCULATED PIN SURFACE TEMPERATURES FOR DATA OBTAINED IN REFERENCE 5

[Calculations done for 25 vol % SiC whisker reinforced also $Al_2O_3$ composite. Wear scar radius ≈1 mm; thermal diffusivity, ≈$1.35\times10^{-5}$ $m^2/s$; thermal conductivity, ≈22.3 W/m °C; F in N, 26.5; Test velocity, 2.7 m/s.]

| $T_{TEST}$ temperature, °C | $\mu$ | $T_{CALCULATED}$ temperature, °C |
|---|---|---|
| 25 | 0.74 | 605 |
| 600 | 0.60 | 1071 |
| 800 | 0.72 | 1365 |
| 1200 | 0.58 | 1655 |

TABLE III. - COMPARISON OF PREDICTED WEAR MODE AND EXPERIMENTALLY DETERMINED WEAR MODE

[Test load, 26.5 N; Test velocity, ≈2.7 m/s.]

| $T_{TEST}$ temperature, °C | $T_{CALCULATED}$ temperature, °C | Mode predicted | Mode observed |
|---|---|---|---|
| 25 | 605 | Whisker fracture | Whisker fracture |
| 600 | 1071 | Transition - mixed mode | Mixed mode |
| 800 | 1365 | Whisker pullout | Whisker pullout |
| 1200 | 1655 | Whisker pullout | Whisker pullout |

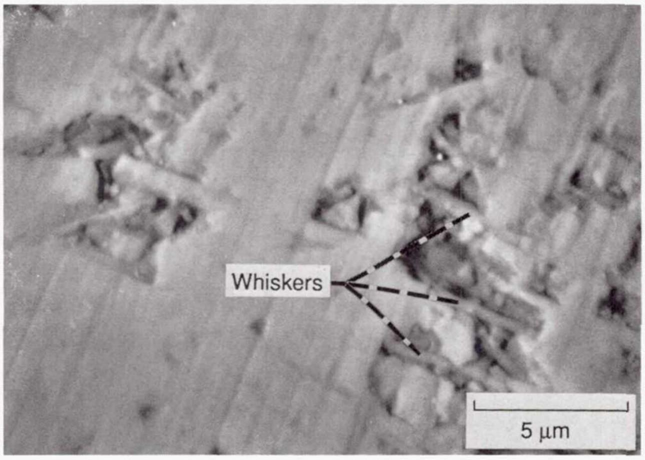


Figure 1.—SEM micrograph of ceramic surface showing orientation of whiskers in planes parallel to surface and sliding plane.

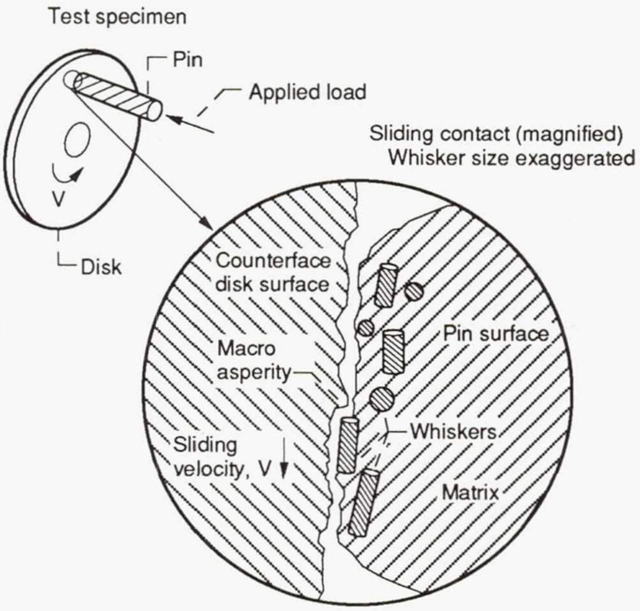


Figure 2.–Pin-on-disk geometry of specimens modeled and an illustration of whisker/asperity interation.

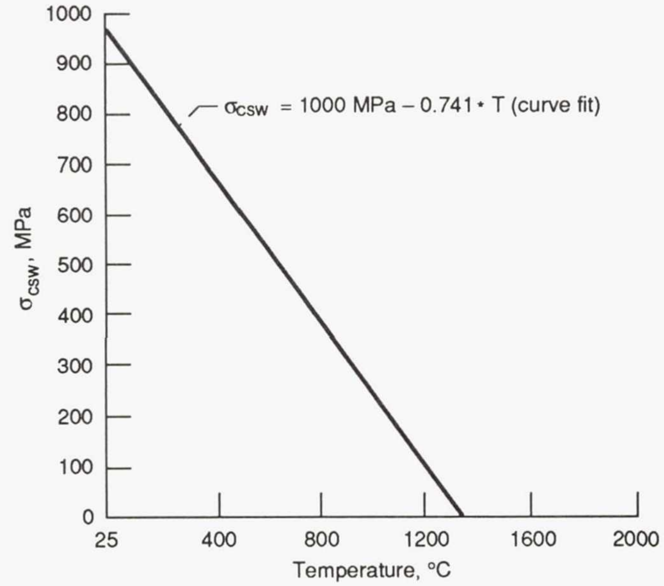


Figure 3.–Variation of maximum residual hoop stresses at whisker surface with temperature. From Ref. 10 for an 18% by vol. $SiC–Al_2O_3$ composite.

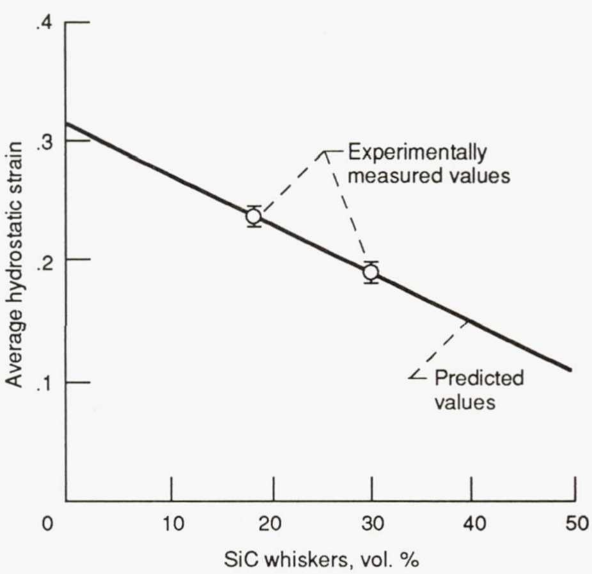


Figure 4.–Compressive strain on SiC whiskers at room temperature as a function of whisker % vol from Ref. 10 Error bars represent one standard deviation of measured data.

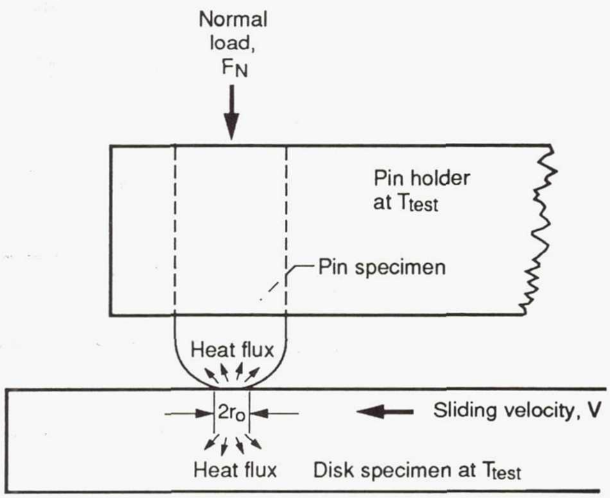


Figure 5.–Sketch of physical situation modelled by heat transfer analysis. Pin and disk specimens have equivatent thermal properties.

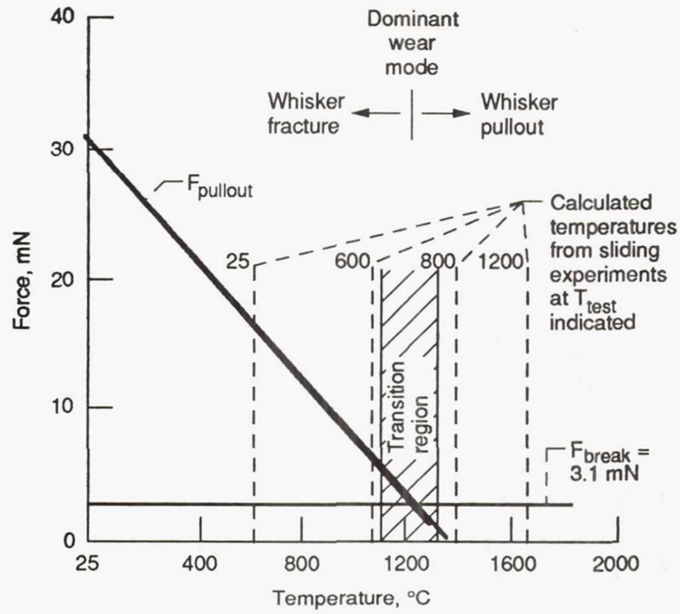


Figure 6.–Variation of whisker fracture force, $F_{break}$, and whisker pullout force, $F_{pullout}$, versus temperature. Wear mode transition occurs at crossover of $F_{pullout}$ and $F_{break}$. Dotted vertical lines represent experiments conducted at ambient temperatures ($T_{test}$) as indicated. Temperature on abscissa may be the result of ambient heating, frictional heating or both.

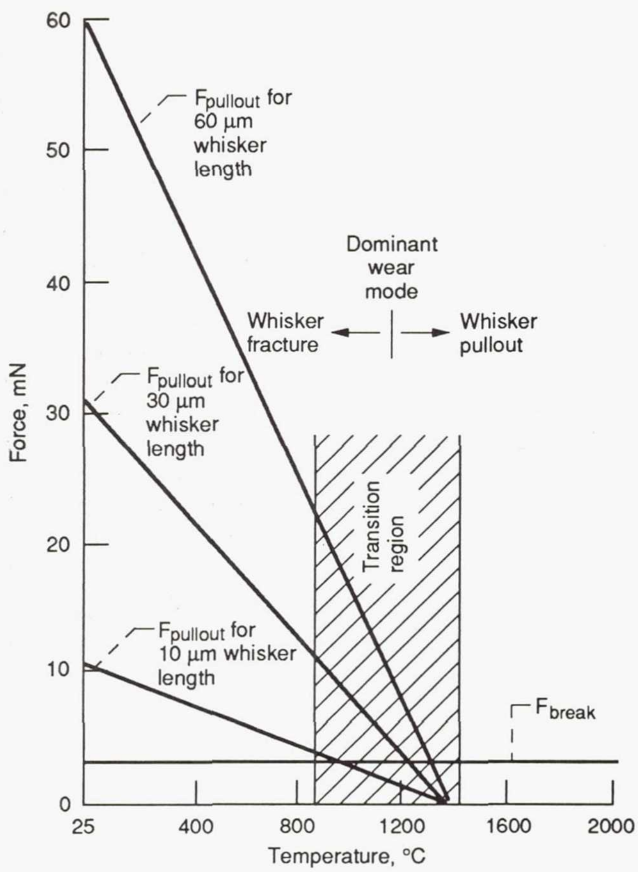


Figure 7.–The effect of average whisker length on $F_{pullout}$ versus temperature. Transition is reduced from 1300 to 950 °C when whisker length is reduced from 60 to 10 µm.

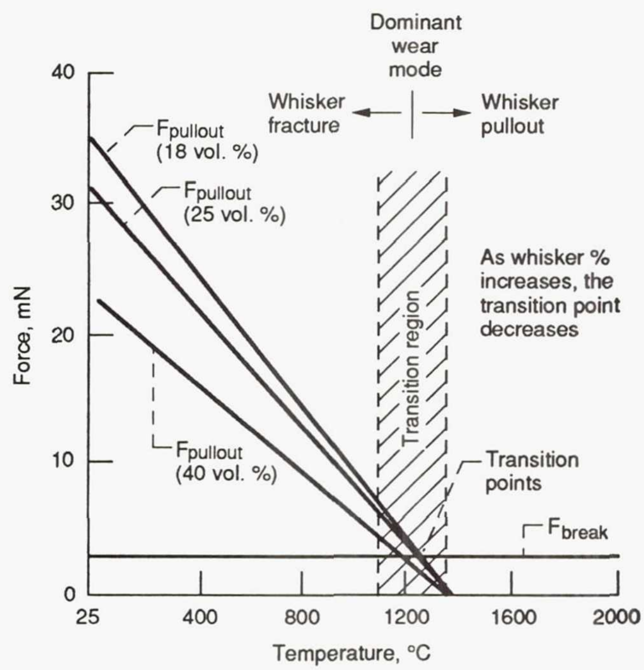


Figure 8.–Variation of transition point as volume percent whisker content changes from 18 to 40 vol % as a function of temperature.

# Report Documentation Page

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15. Supplementary Notes

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16. Abstract

The following paper describes a model for predicting the wear behavior of whisker reinforced ceramics. The model has been successfully applied to a silicon carbide whisker reinforced alumina ceramic composite subjected to sliding contact. The model compares the frictional forces on the whiskers due to sliding, which act to pull or push them out of the matrix, to the clamping or compressive forces on the whiskers due to the matrix, which act to hold the whiskers in the composite. At low temperatures, the whiskers are held strongly in the matrix and are fractured into pieces during the wear process along with the matrix. At elevated temperatures differential thermal expansion between the whiskers and matrix can cause "loosening" of the whiskers and lead to pullout during the wear process and to higher wear. The model, which represents the combination of an elastic stress analysis and a friction heating analysis, predicts a transition temperature at which the strength of the whiskers equals the "clamping" force holding them in the matrix. Above the transition the whiskers are pulled out of the matrix during sliding, and below the transition the whiskers are simply fractured. The existence of the transition gives rise to a dual wear mode or mechanism behavior for this material which has been observed in laboratory experiments. The results from this model correlate well with experimentally observed behavior indicating that the model may be useful in obtaining a better understanding of material behavior and in making material improvements.

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